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Kinematic Range of Motion Analysis for a High Degree-of-Freedom Unmanned Ground Vehicle

*B. Beckman and M. Trentini
DRDC Suffield*

Defence R&D Canada

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Principal Author
Original signed by Blake Beckman

Blake Beckman

Approved by
Original signed by D.M. Hanna

D.M. Hanna
Head/AISS

Approved for release by
Original signed by Dr P.A. D'Agostino

Dr P.A. D'Agostino
DRP Chair

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Abstract

The requirement for increased mobility of unmanned ground vehicles operating in urban settings must be addressed if robotic technology is to augment human efforts in military relevant roles and environments. In preparation for this role, Defence R&D Canada – Suffield is exploring novel mobility platforms that use intelligent mobility algorithms to improve robot mobility in unknown highly complex terrain. The Autonomous Intelligent Systems Section at Defence R&D Canada – Suffield commissioned the development of a high degree-of-freedom robot for control algorithm development. The Micro Hydraulic Toolkit vehicle is a hydraulically-driven vehicle with modular structural and actuator components. This modularity allows for the selection of many different degree-of-freedom configurations for the vehicle. The focus of this paper is to present a range of motion analysis for five different vehicle configurations. The objective of conducting this analysis is to determine the maximum height the wheel can achieve from the ground for each of the selected vehicle configurations. The maximum achievable wheel height will provide the foundation for research into the most advantageous vehicle configuration for obstacle traversing. The homogeneous transformation is used to calculate the vehicle's range of motion and is displayed in a planar graphical plot. This data reveals the maximum attainable wheel height of the vehicle given a level main body. Further calculations reveal the maximum wheel height with an inclined body.

Résumé

Il faut augmenter la mobilité des véhicules terrestres sans équipage opérant en contexte urbain pour que la technologie de la robotique soit en mesure d'augmenter les efforts humains en réponse aux rôles et environnements de l'armée. En préparation à ces rôles, R & D pour la défense Canada – Suffield explore actuellement les nouvelles plateformes de mobilité qui utilisent les algorithmes de mobilité intelligente pour améliorer la mobilité robotique sur des terrains inconnus et hautement complexes. La Section des Systèmes intelligents autonomes de R & D pour la défense Canada – Suffield a commandé la mise au point d'un robot avec haut degré de liberté pour le développement des algorithmes de commande. Le véhicule Micro Hydraulic Toolkit est un véhicule à conduite hydraulique ayant une structure modulaire et les composantes d'un terminal. Cet article focalise sur la présentation d'une série d'analyses des mouvements de cinq différentes configurations de véhicules. L'objectif de la conduite de ces analyses et de déterminer la hauteur maximum possible des roues au sol pour chacune des configurations de véhicules sélectionnées. La hauteur maximum possible de la roue sera la base de la recherche sur la configuration la plus avantageuse d'un véhicule en matière de traversée des obstacles. On utilise la transformation homogène affichée sur un graphe planaire pour calculer l'amplitude des mouvements du véhicule. Ces données révèlent la hauteur maximum que la roue d'un véhicule peut atteindre quand le corps du véhicule est à niveau. Des calculs supplémentaires révèlent la hauteur maximum de la roue quand le corps du véhicule est incliné.

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Executive summary

Kinematic Range of Motion Analysis for a High Degree-of-Freedom Unmanned Ground Vehicle

B. Beckman and M. Trentini

DRDC Suffield TM 2009-231; Defence R&D Canada – Suffield; December 2009.

Defence R&D Canada – Suffield conducts research in Unmanned Ground Vehicle (UGV) intelligence for mobility in complex terrain. The research methodology addresses the numerous challenges and uncertainties that complicate the design of UGV systems. Firstly, distinct vehicle paradigms are formulated in an attempt to conduct research that addresses the large complex space of relevant military UGVs. Next, vehicles are configured that represent each of the distinct paradigm classes, allowing each vehicle to handle their environment in a different way with different capabilities. The intent is not the design of particular optimal robots for specific missions, but rather to allow research to be conducted in the many areas of mobility, so that solutions to UGV locomotion are more robust. The high dexterity mobility paradigm is being addressed by a 12 degree-of-freedom hybrid legged/wheeled vehicle, the Micro Hydraulics Toolkit (MHT).

The Micro Hydraulics Toolkit platform was designed to have a modular construction, which will allow increasingly complex vehicles to be created. The structural leg members connecting the hip to knee and knee to wheel are designed to be fastened in 22.5 degree increments. This modularity provides extensive flexibility but creates complexity in the selection of optimal appendage configurations.

To reduce the problem to a manageable level, some restrictions were placed on the configurations. The vehicle must be statically stable, symmetrical both front and back as well as left to right, and the starting positions of the wheels must not interfere with each other. Five different vehicle configurations were chosen and the kinematic range of motion envelope for each leg actuator was analyzed to maximize height with both a level main body and an inclined main body. This maximum height determines the largest obstacle the robot could traverse. The most advantageous obstacle traversing configuration is when the hip position of the front legs is at 45 degrees while the knee position is at 45 degrees. This position allows the wheel to reach the greatest height with main body level and the second highest with an inclined body. This configuration also maximizes the working envelope of the end effector in height and reach from the hip socket.

Sommaire

Kinematic Range of Motion Analysis for a High Degree-of-Freedom Unmanned Ground Vehicle

B. Beckman and M. Trentini

DRDC Suffield TM 2009-231; R & D pour la défense Canada – Suffield;
Décembre 2009.

R & D pour la défense Canada – Suffield conduit la recherche dans le domaine de l'intelligence des véhicules terrestres sans équipage (UGV) en matière de mobilité sur des terrains complexes. La méthodologie de la recherche traite des nombreux défis et incertitudes qui compliquent le concept des systèmes UGV. On formule d'abord des paradigmes distincts de véhicules pour tenter de conduire une recherche qui tient compte des grands espaces complexes dans lesquels se déplacent les UGV militaires. Puis, les véhicules sont configurés de manière à représenter chacune des classes de paradigmes distincts ce qui permet à chaque véhicule de gérer son environnement d'une manière différente selon ses différentes capacités. Il ne s'agit pas de concevoir des robots à rendement optimal particulier pour des missions spécifiques mais plutôt d'être en mesure de conduire la recherche dans beaucoup de domaines de mobilité de manière à ce que les solutions relatives à la locomotion UGV soient plus robustes. Le paradigme de la mobilité de haute dextérité a été abordé avec le Micro Hydraulics Toolkit (MHT), un véhicule hybride avec roues sur jambes ayant 12 degrés de liberté.

La plateforme du Micro Hydraulics Toolkit a été conçue avec une construction modulaire qui permettra de créer des véhicules de plus en plus complexes. Les parties structurelles de la jambe qui joignent la hanche au genou et le genou à la roue sont conçues pour être attachées en incréments de 22,5 degrés. Cette modularité augmente la flexibilité mais complique la sélection des configurations optimales des appendices.

Pour mieux gérer le problème, on a mis des restrictions sur certaines configurations. Le véhicule doit être stable statiquement, le devant et le derrière doivent être symétrique de même que les côtés droit et gauche et les positions de départ des roues ne doivent pas interférer entre elles. On a choisi cinq différentes configurations de véhicules et l'enveloppe de l'amplitude du mouvement cinématique de chaque vérin de manœuvre de la jambe a été analysée pour maximiser la hauteur, que le corps du véhicule soit à niveau ou qu'il soit incliné. La hauteur maximum détermine la grosseur maximum de l'obstacle que le robot peut traverser. La configuration maximum de traversée d'un obstacle la plus avantageuse est quand la position des hanches et des jambes avant est à 45 degrés avec la position des genoux à 45 degrés. Cette position permet à la roue d'atteindre sa hauteur maximum quand le corps du véhicule est à niveau et la seconde hauteur avec le corps incliné. Cette configuration maximise aussi le champ d'intervention du terminal en hauteur et en portée avec la cavité articulaire des hanches.

Table of contents

| | |
|---|-----|
| Abstract | i |
| Résumé | i |
| Executive summary | iii |
| Sommaire | iv |
| Table of contents | v |
| List of figures | vi |
| List of tables | vii |
| 1 Introduction | 1 |
| 2 Kinematic Analysis of the Micro Hydraulic Toolkit | 2 |
| 3 Envelope of operation for wheel end effector | 5 |
| 4 Discussion | 12 |
| 5 Conclusions | 12 |
| References | 13 |

List of figures

| | | |
|------------|---|----|
| Figure 1: | Micro Hydraulic Toolkit control research vehicle. | 1 |
| Figure 2: | Micro Hydraulic Toolkit solid model. | 3 |
| Figure 3: | Micro Hydraulic Toolkit coordinate representation. | 3 |
| Figure 4: | Complete MHT Leg Assembly and Main Structure (mm) | 6 |
| Figure 5: | MHT cross section with wheel end effector trajectory for Config. 1. | 7 |
| Figure 6: | MHT cross section with wheel end effector trajectory for Config. 2. | 7 |
| Figure 7: | MHT cross section with wheel end effector trajectory for Config. 3. | 8 |
| Figure 8: | MHT cross section with wheel end effector trajectory for Config. 4. | 8 |
| Figure 9: | MHT cross section with wheel end effector trajectory for Config. 5. | 8 |
| Figure 10: | Max Wheel Height with Config. 1 Range of Motion. | 9 |
| Figure 11: | Max Wheel Height with Config. 2 Range of Motion. | 9 |
| Figure 12: | Max Wheel Height with Config. 3 Range of Motion. | 10 |
| Figure 13: | Max Wheel Height with Config. 4 Range of Motion. | 10 |
| Figure 14: | Max Wheel Height with Config. 5 Range of Motion. | 11 |

List of tables

| | | |
|----------|---|----|
| Table 1: | Front Left Leg Actuator Positions | 5 |
| Table 2: | Maximum wheel height | 11 |

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1 Introduction

As military conflicts shift from open terrain operations to the increased complexity of urban settings, it is expected that the mobility requirement for Unmanned Ground Vehicles (UGVs) will increase [1]. The obstacles encountered in a military urban setting pose great mobility challenges. Initial work has been completed in urban terrain classification for military operations, but little work has been done to control novel vehicles in these unstructured terrains [2]. The Autonomous Intelligent Systems Section at Defence R&D Canada - Suffield is exploring the development of intelligent mobility algorithms for novel UGVs. Intelligent mobility algorithms exploit the UGV's inherent dexterity and available world representation of the environment using learning and control theory to engage extremely cluttered environments [3].



Figure 1: *Micro Hydraulic Toolkit control research vehicle.*

The Micro Hydraulic Toolkit vehicle (MHT) will be used as a research tool to pursue intelligent mobility algorithm development. The vehicle is a reconfigurable platform with 12 controllable degrees-of-freedom. As shown in the Figure 1, the UGV has a main structure that houses the pump, motor, battery, and control electronics. Using a biological analogy, the main structure also houses a rotary actuator, or *hip*, that connects to another rotary actuator, or *knee*, by means of a structural leg member, or *femur*. The rotary knee actuator connects to a rotary wheel by another structural member, or *tibia*. The entire toolkit is designed with 12 degrees-of-freedom, operated by 8 hydraulic actuators and 4 electric actuators. The four hip and four knee actuators are non-continuous rotary hydraulic actuators that are capable of 90 degrees of rotation. The vehicle is intended to be reconfigurable and therefore the structural members connecting hip to knee and knee to wheel are designed to be fastened in 22.5 degree increments. The four electric wheel actuators are capable of continuous

rotary motion. Dimensions in the standing position are approximately one meter in length, width and height.

Identifying the kinematic range of motion and maximum achievable wheel height provides the information needed for traversing large obstacles. The main structure of the vehicle is designed so that the hip and knee actuators on either side of the vehicle are in the same plane. This paper uses five discrete starting positions for the hip and knee actuators that are chosen to indicate the different working envelopes of the wheel end effectors. These different working envelopes provide the data to determine the maximum wheel height given a level body, as well as an inclined body.

2 Kinematic Analysis of the Micro Hydraulic Toolkit

The homogeneous transformation, calculated for the MHT, is used to solve the wheel end effector position for hip and knee actuator values. MATLAB is used to iterate the solution to give multiple data points for the planar graphical plot. The first quarter of the working envelope is created by holding the knee actuator constant at its starting position and plotting the end effector position as the hip moves from its start position to its end position. The second quarter of the envelope is created from holding the hip actuator constant at its end position and plotting the end effector position as the knee moves from its start position to its end position. The third quarter of the working envelope is created by holding the knee actuator constant at its end position and plotting the end effector position as the hip moves from its end position to its start position. The fourth quarter of the working envelope is created by holding the hip actuator constant at its starting position and plotting the end effector position as the knee moves from its end position to its start position.

To calculate the homogeneous transformation the right hand coordinate system must be assigned to the vehicle. A MSC.visualNastran Motion model of the toolkit is used to visualize the coordinate frames of the vehicle as well as display the simulation of the vehicle's range of motion. The solid model is shown in Figure 2 with the arrows of the coordinate systems showing through the solid model. The coordinate frames shown on the toolkit in Figure 3 show the right hand coordinate systems applied for each rotary actuator according to the Denavit-Hartenberg (D-H) convention [4]. For simplicity however, the figure only shows the front left leg labeled. The structural members and non-continuous hydraulic actuators of the vehicle are identical and thus the homogeneous transformation is identical for all legs. In contrast, the starting positions for the hip and knee actuators are not identical and must be calculated from the coordinate frame. The transformation matrix is calculated for the wheel end effector, frame 2, relative to the hip, frame 0, on the main structure.

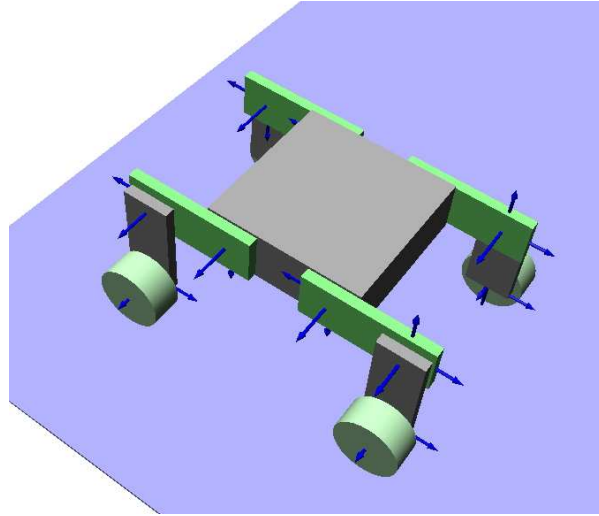


Figure 2: *Micro Hydraulic Toolkit solid model.*

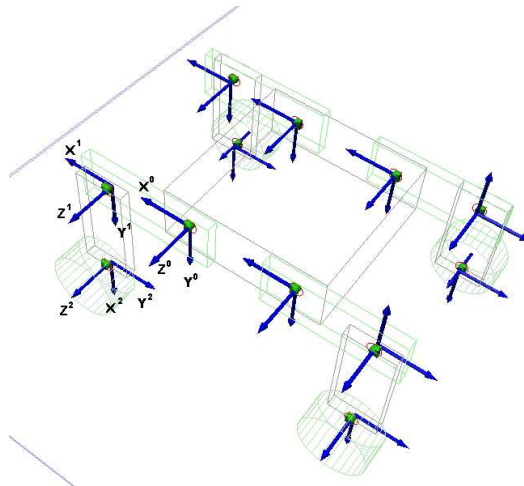


Figure 3: *Micro Hydraulic Toolkit coordinate representation.*

The variable q is defined as the positive rotation of the joint, defined by the right hand rule. The MHT vehicle, shown in Figure 3, is illustrated in a configuration that easily determines the rotational value of q . The rotational joints of the front left leg, which is labeled according to the D-H convention, are at the same position of the rotational joints of the front right leg. The hip position of the front legs are at 0 degrees while the knee positions of the front legs are at 90 degrees. The rotational

joints of the rear left leg are also at the same position as those of the rear right leg. The hip position of the rear legs are at 180 degrees while the knee positions of the rear legs are at -90 degrees.

The homogeneous transformation is calculated for the front left leg and shown as function q . The subscript or superscript of each variable in the equations or figures are related to their coordinate frames. Equation 1 is used to simplify the transformation matrices [5].

$$\begin{aligned} C_{ab} &= \cos(q_a + q_b) = \cos(q_a)\cos(q_b) - \sin(q_a)\sin(q_b) \\ S_{ab} &= \sin(q_a + q_b) = \sin(q_a)\cos(q_b) + \cos(q_a)\sin(q_b) \end{aligned} \quad (1)$$

Equation (2) shows the homogenous transformation matrix of frame 1 with respect to frame 0 and as a function of q_1 with A_1 representing the length of the femur.

$$H_0^1 = \begin{bmatrix} C_1 & -S_1 & 0 & A_1C_1 \\ S_1 & C_1 & 0 & A_1S_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

Equation (3) shows the homogenous transformation matrix of frame 2 with respect to frame 1 and as a function of q_2 with A_2 representing the length of the tibia.

$$H_1^2 = \begin{bmatrix} C_2 & -S_2 & 0 & A_2C_2 \\ S_2 & C_2 & 0 & A_2S_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

$$H_0^2 = \begin{bmatrix} C_{12} & -S_{12} & 0 & A_2C_{12} + A_1C_1 \\ S_{12} & C_{12} & 0 & A_2S_{12} + A_1S_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

The matrix product of equation 2 and equation 3 reveals the matrix in equation 4 which is simplified by the trigonometric identities. This equation is used in MATLAB to iterate forward kinematic solutions for all values of q . The non-continuous rotary hip and knee actuators have an operating range of 90 degrees and the structural

members can be assembled in 22.5 degree increments. This information along with the dimensions of the structural members will be used to determine the operational envelope of the wheel end effector.

3 Envelope of operation for wheel end effector

The operational envelope is defined as the area of points in space created by the wheel end effector. The wheel reaches different points in space when the actuators move through their range while connected to the structural members. MATLAB is used to iterate the solution and display multiple data points given the starting positions and operating range of each of the actuators, as well as the lengths of the femur and tibia. The femur is 0.315 m long from the center of the hip to the center of the knee and the tibia is 0.377 m long from the center of the knee to the center of the wheel. The two left hips on the body are in the same plane and are located 0.3 m from the center of one actuator to the center of the other actuator.

Table 1: Front Left Leg Actuator Positions

| | | Start Position (degrees) | Joint Rotation (degrees) | End Position (degrees) |
|-----------------------|------|-----------------------------|-----------------------------|---------------------------|
| Fig. 5 (Config. 1) | hip | 90.0 | -90.0 | 0.0 |
| | knee | 0.0 | 90.0 | 90.0 |
| Fig. 6 (Config. 2) | hip | 67.5 | -90.0 | -22.5 |
| | knee | 22.5 | 90.0 | 112.5 |
| Fig. 7 (Config. 3) | hip | 45.0 | -90.0 | -45.0 |
| | knee | 45.0 | 90.0 | 135.0 |
| Fig. 8 (Config. 4) | hip | 22.5 | -90.0 | -67.5 |
| | knee | 67.5 | 90.0 | 157.5 |
| Fig. 9 (Config. 5) | hip | 0.0 | -90.0 | -90.0 |
| | knee | 90.0 | 90.0 | 180.0 |

The operating envelope that is displayed in a planar graphical plot has the limiting condition that the main body must remain level. Other limiting conditions are that the legs must move in a symmetrical motion with the right side mirroring the left side of the vehicle and the starting position of the wheels must not interfere with each other. Further, the wheels must be able to move under the main structure of the vehicle so the vehicle maintains the ability to generate motion. Table 1 shows the starting positions of the hip and knee actuators of the front left leg, the direction of rotation of the actuator and its final position. The front and rear legs move in a

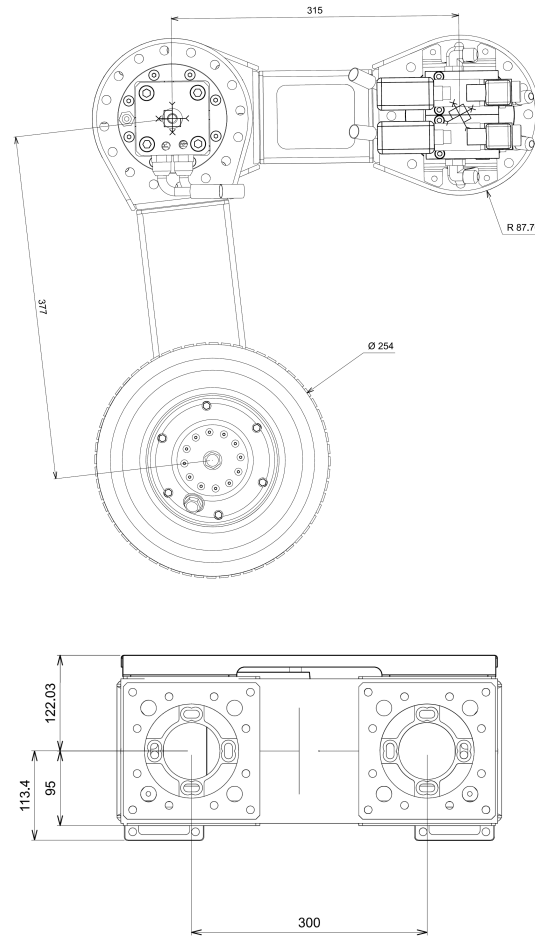


Figure 4: Complete MHT Leg Assembly and Main Structure (mm)

symmetrical motion and the five starting positions of the knee and hip actuators will be referred to as a specific configuration. As shown in Table 1 on the left hand side these configurations will be Config. 1 through Config. 5.

The plot is generated to show the maximum and minimum positions of the wheel end effector in the limits of rotation and shows the recorded positions. The five plots depicted in Figures 5 – 9 show the planar view of the MHT with the starting and finishing position being the same value. The envelope that is marked by o defines the operating range of the center of the wheel end effector. As illustrated in the graphs the operating range envelope becomes narrower and taller as the start configurations progress from Figure 5; to Figure 9. This data is used to determine the maximum possible wheel height given a level and non-level body.

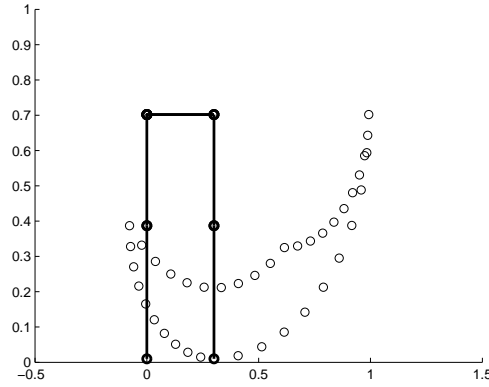


Figure 5: MHT cross section with wheel end effector trajectory for Config. 1.

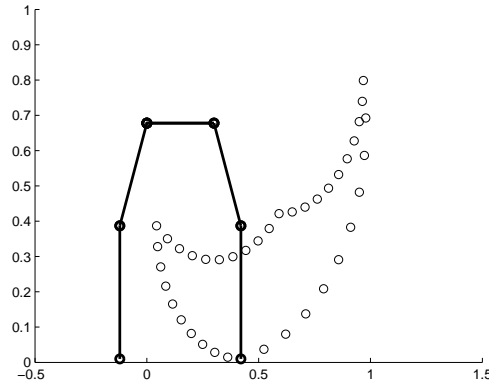


Figure 6: MHT cross section with wheel end effector trajectory for Config. 2.

The maximum achievable wheel height, with the main body remaining level, is determined from the vehicle geometry in the standing position with one leg raised to its extreme. It is shown as the highest mark in Figure 5 through to Figure 9. The maximum achievable wheel height, without the main body remaining level, is also calculated from the geometry. The UGV's hind legs are stretched out behind with one leg placed in its down position as a support while the other leg is extended to its extreme. The vehicle configurations are shown in Figures 10 – 14 to give the reader a better understanding of the intended configuration. Table 2 shows the different vehicle heights and maximum wheel heights with and without a level main body.

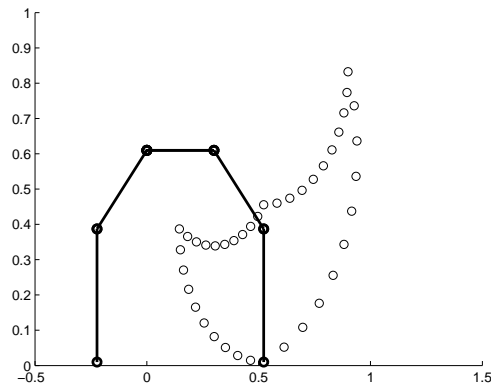


Figure 7: MHT cross section with wheel end effector trajectory for Config. 3.

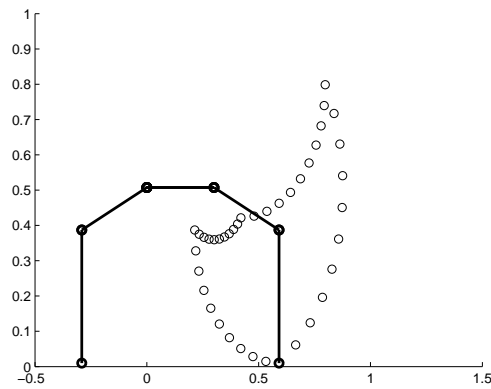


Figure 8: MHT cross section with wheel end effector trajectory for Config. 4.

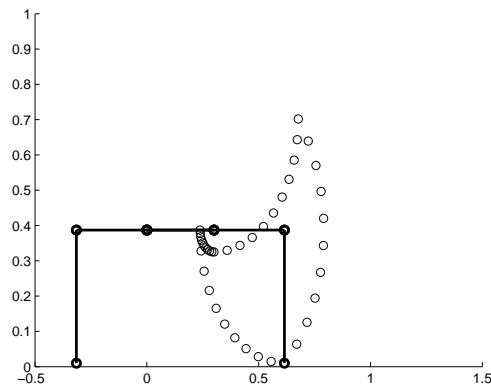


Figure 9: MHT cross section with wheel end effector trajectory for Config. 5.

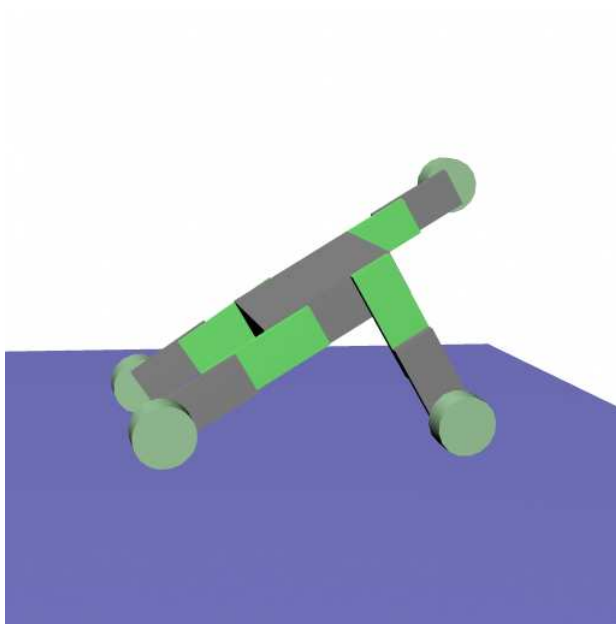


Figure 10: Max Wheel Height with Config. 1 Range of Motion.

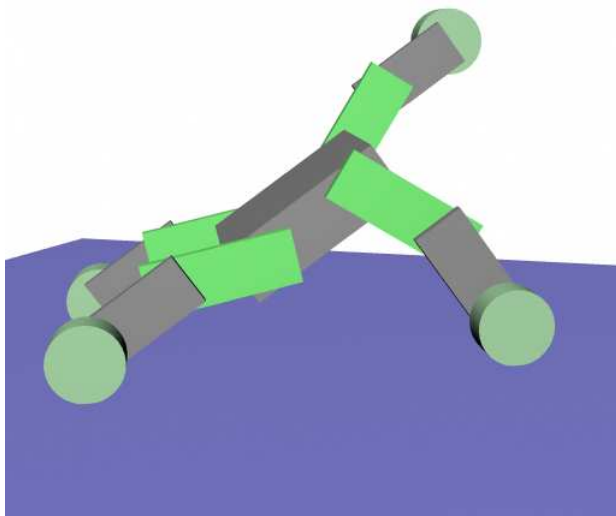


Figure 11: Max Wheel Height with Config. 2 Range of Motion.

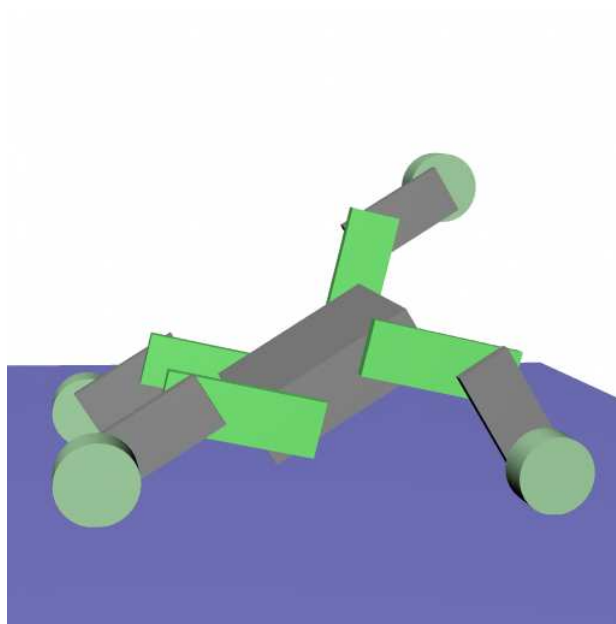


Figure 12: Max Wheel Height with Config. 3 Range of Motion.

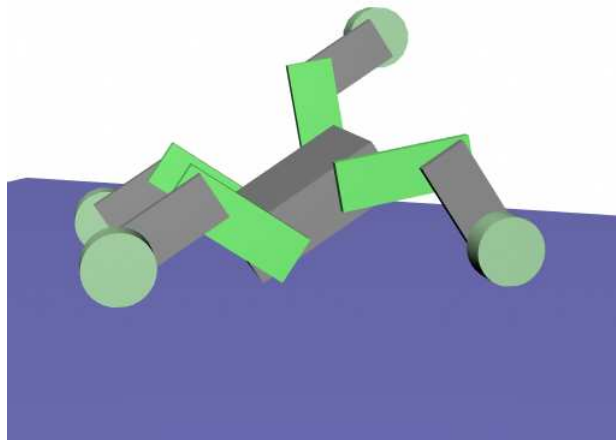


Figure 13: Max Wheel Height with Config. 4 Range of Motion.

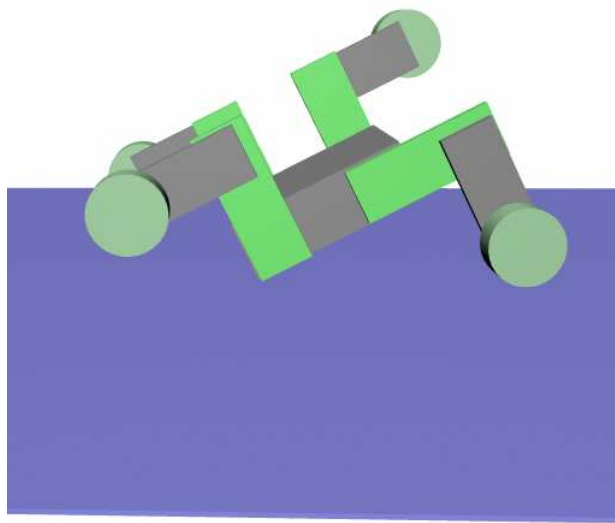


Figure 14: Max Wheel Height with Config. 5 Range of Motion.

Table 2: Maximum wheel height

| | Maximum Vehicle Height (meters) | Maximum Wheel Height - level (meters) | Maximum Wheel Height - non level (meters) |
|-----------|---------------------------------|---------------------------------------|---|
| Config. 1 | 0.70 | 0.70 | 0.927 |
| Config. 2 | 0.68 | 0.80 | 0.956 |
| Config. 3 | 0.60 | 0.83 | 0.921 |
| Config. 4 | 0.50 | 0.80 | 0.831 |
| Config. 5 | 0.38 | 0.70 | 0.697 |

4 Discussion

The homogeneous transformation was calculated for the wheel end effector with respect to the hip. This analysis allowed for the determination of the operating envelope of the wheel end effector for five different starting configurations. As shown in the five planar plots the operating range envelope gets narrower and taller as the start configurations progress from Figure 5 through Figure 9. This reveals that straight-line trajectory planning would be more difficult for the narrow operating envelopes.

The maximum achievable wheel height while the main body remains level occurs in configuration three. However, the maximum achievable wheel height with the main body at an incline occurs in configuration two. This reveals that the most advantageous obstacle traversing configuration could be configuration two, given that it has higher achievable wheel height; however, the operating envelope is narrower, which would limit the obstacle size it could step over.

5 Conclusions

This paper addressed the kinematic range of motion for the Micro Hydraulic Toolkit. Specifically, it determined the operating envelope of the wheel end effector for five different leg configurations. As shown in the five plots the operating range envelope gets narrower and taller as the start configurations progress from Figure 5 through Figure 9. The maximum wheel height was calculated from this data with both a level and inclined main body. It was determined that the maximum wheel height, with the main body level, occurred in configuration three with a height of 0.83 meters. A wheel height of 0.956 meters was achieved in configuration two with an inclined body. This reveals that the most advantageous configuration that maximize wheel end effector height while providing an taller overall working envelope is Config. 3. This configuration will be used as the standard position of the MHT robot, as it maximizes the obstacle the robot can potentially overcome.

Future work for the MHT involves solving the velocity kinematics problem and end effector trajectory planning. This work will provide the foundation to determine the dynamics of the legs of the vehicle. Leg dynamics will define the required torque that is needed to move the wheel end effector at a specific rate. This information will help to determine the performance requirements of the hip and knee actuators.

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The requirement for increased mobility of unmanned ground vehicles operating in urban settings must be addressed if robotic technology is to augment human efforts in military relevant roles and environments. In preparation for this role, Defence R&D Canada – Suffield is exploring novel mobility platforms that use intelligent mobility algorithms to improve robot mobility in unknown highly complex terrain. The Autonomous Intelligent Systems Section at Defence R&D Canada – Suffield commissioned the development of a high degree-of-freedom robot for control algorithm development. The Micro Hydraulic Toolkit vehicle is a hydraulically-driven vehicle with modular structural and actuator components. This modularity allows for the selection of many different degree-of-freedom configurations for the vehicle. The focus of this paper is to present a range of motion analysis for five different vehicle configurations. The objective of conducting this analysis is to determine the maximum height the wheel can achieve from the ground for each of the selected vehicle configurations. The maximum achievable wheel height will provide the foundation for research into the most advantageous vehicle configuration for obstacle traversing. The homogeneous transformation is used to calculate the vehicle's range of motion and is displayed in a planar graphical plot. This data reveals the maximum attainable wheel height of the vehicle given a level main body. Further calculations reveal the maximum wheel height with an inclined body.

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Unmanned Ground Vehicle, Kinematic, Model

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